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Title: The Scientific Challenges in Stewarding the U.S. Nuclear Weapons Stockpile

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The Scientific Challenges in Stewarding the U.S. Nuclear Weapons Stockpile

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LANL Stewards Much of the U.S. Nuclear Stockpile

- We are the design agency for four of seven weapons systems in the national arsenal
- We are responsible for the safety, surety, and reliability of these systems

W78 land-based warhead

B61 aircraft-carried bomb

W76/W88 sub-based warheads

Since 1992, we have performed our mission without nuclear testing

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Nuclear Weapons Release Nuclear Binding Energy

- Both heavy-nuclei fission and light-nuclei fusion release energy
- Fission releases $\sim$ 200 MeV per fission event
  - Example: $n + {}^{235}\text{U} \rightarrow {}^{236}\text{U} \rightarrow {}^{92}\text{Kr} + {}^{141}\text{Ba} + 3n$
  - Note that additional neutrons are produced, inducing further fissions
- Fusion produces 17.6 MeV per fusion (for D+T)
  - Example: $\text{D} + \text{T} \rightarrow {}^{4}\text{He} + n$
- Compare to chemical reactions that release eV's per reaction event

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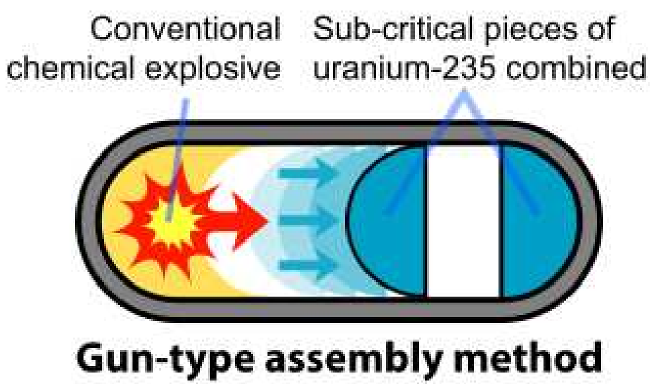
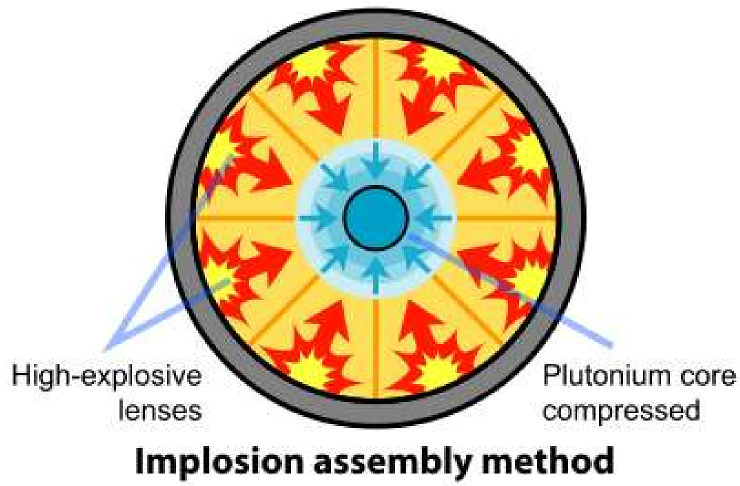
Early Nuclear Weapons Used Only Fission

- Function by creating a super-critical mass (neutron leakage rate $<$ production rate)
- Two technologies were developed by LANL during the Manhattan Project
- Gun weapon assembles sub-critical pieces of fissile material into super-critical mass
- Implosion weapon compresses sub-critical piece of fissile material into super-critical mass





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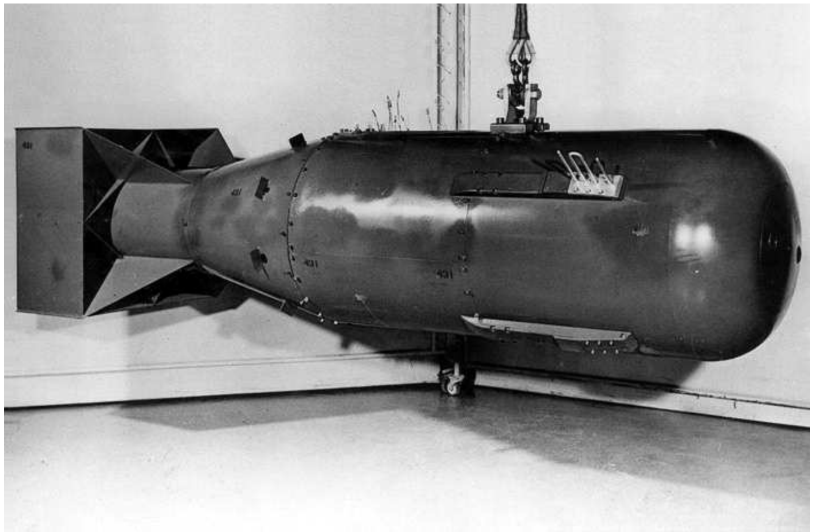
Little Boy Was the First Gun-Assembled Weapon

- Simple design (no proof test required)
- Limited to ^{235}U to avoid pre-initiation
- Inefficient use of nuclear material
- Hiroshima – August 6, 1945
- Yield of 15 kt



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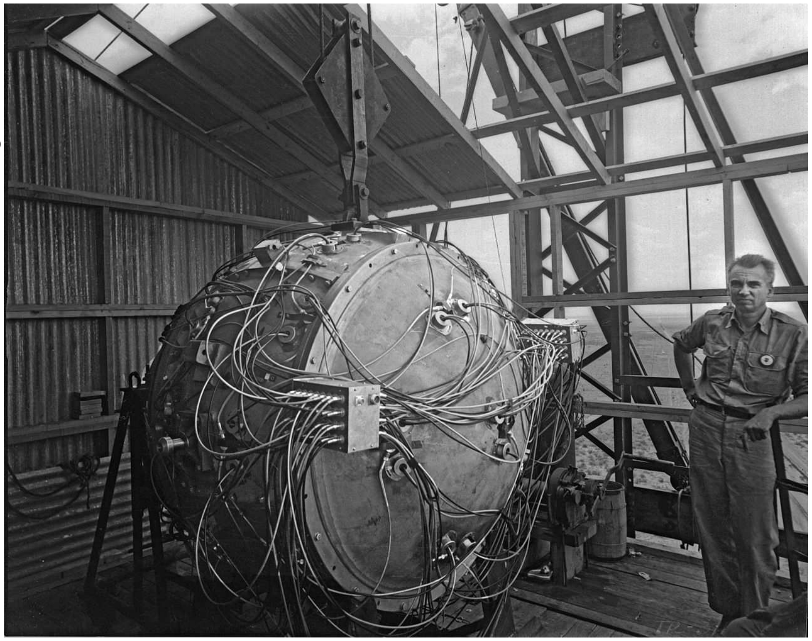
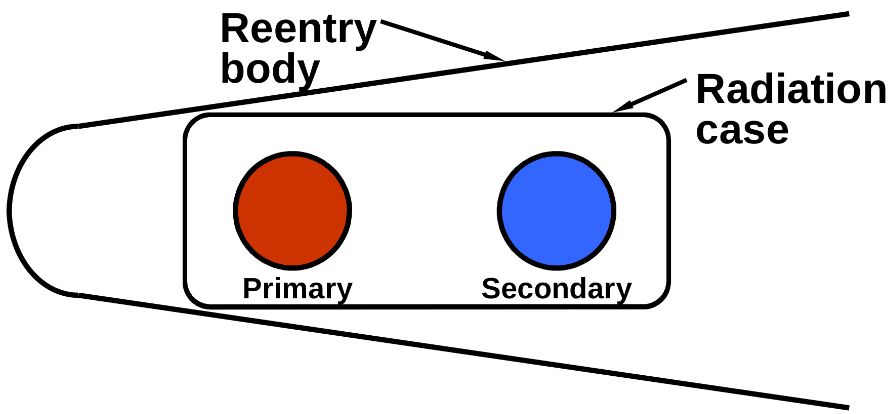
Trinity/Fat Man Was the First Gun-Assembled Weapon

- Complex design using precision explosives
- Can use ^{235}U or ^{239}Pu
- Efficient use of nuclear material
- Trinity – July 16, 1945
- Nagasaki – August 9, 1945
- Yield of 21 kt



Modern Weapons are Thermonuclear



- Thermonuclear weapons have two physically separate stages: primary and secondary
- The primary fission stage goes off first, followed by the secondary stage
- X-ray energy produced by the primary stage heats and compresses the secondary stage
- The device produces energy by fission and fusion
- Much higher yields possible

Ivy/Mike Was the First Thermonuclear Test

- Experimental device
- Used liquid D_2 as TN fuel
- Not suitable as a weapon
- Enewetok – October 31, 1952
- Yield of 10.4 Mt

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Castle/Bravo Was the Largest U.S. Nuclear Test

- Bikini – February 28, 1954
- Predicted yield of 6 MT
- Actual yield of 15 Mt

World Record for Largest Nuclear Test Held by USSR

- "Tsar Bomba"
- Novaja Zemlya – October 30, 1961
- Design Yield 100 Mt
- Tested at reduced yield of 58 Mt

Atmospheric testing was banned by treaty in 1963

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Current U.S. Stockpile Was Designed for Cold War

- Designed for maximum yield in minimum size and weight
  - Highly optimized
- Intended to be replaced after 15–20 years
  - Now well past original design life
- Use hazardous materials
  - Expensive and difficult to handle today
- Very complex, with many parts
  - Challenging to maintain without nuclear testing

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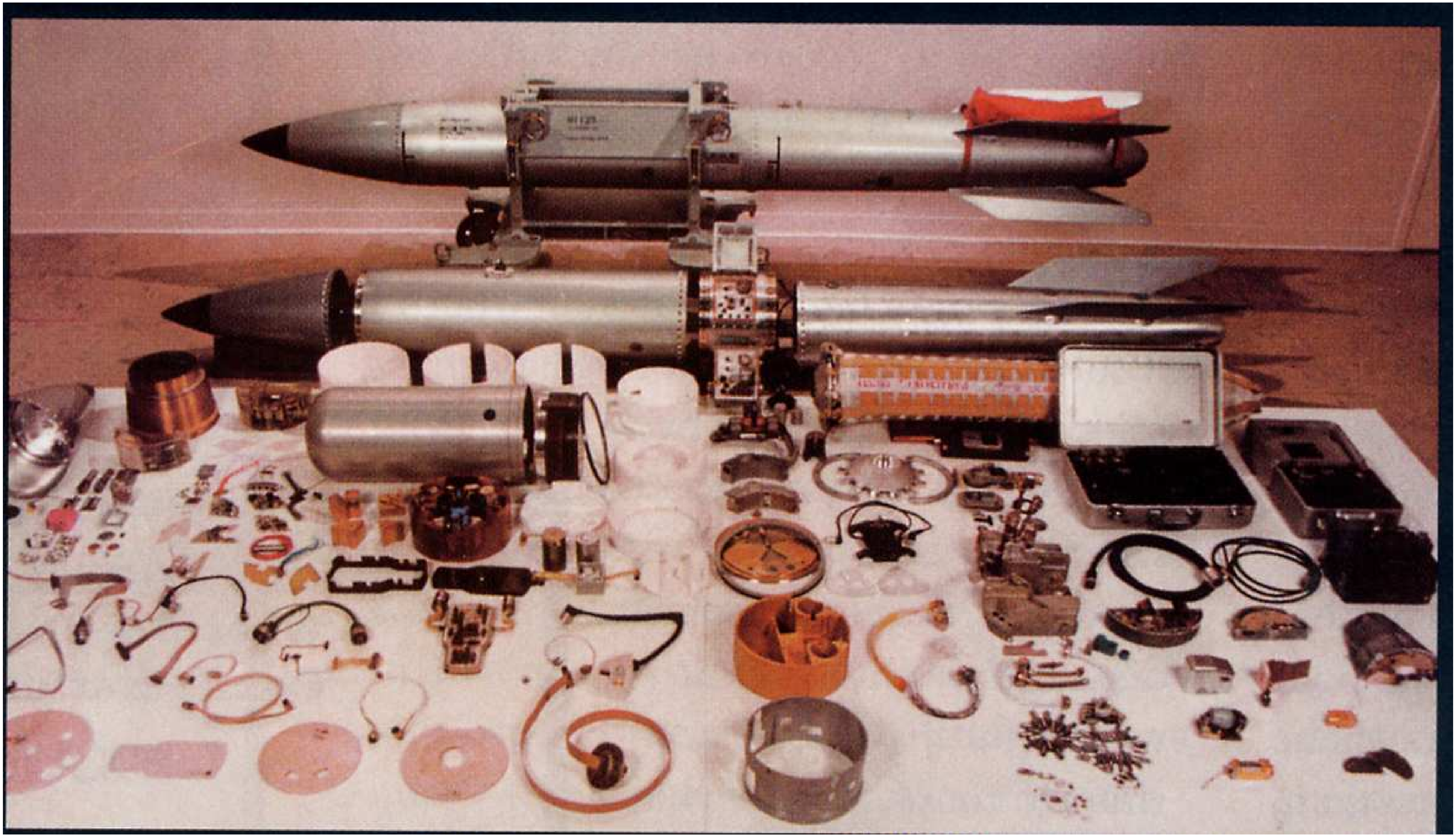
B61 Nuclear Bomb has More Than 4000 Parts



Why is Maintaining the Stockpile So Hard?

- Operating conditions of a nuclear weapon exist nowhere else and cannot be fully replicated in a lab setting
  - Temperatures $> 10^8$ K
  - Material velocities $> 10^6$ m/s
  - Pressures $> 10^7$ bar
  - Time scales $< 10^{-8}$ s
- We have developed a science-based method to stewarding the stockpile
  - Use large-scale multi-physics simulations to predict weapon performance
  - Perform small-scale experiments to continuously improve our understanding of the relevant physics
  - Validate the simulations against legacy test data and integrated non-nuclear and sub-critical experiments
- We also have a surveillance to monitor for unexpected changes

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Computer Simulations of Nuclear Weapons

- We use computational models
  - High explosive burn
  - Radiation/Hydrodynamics
  - Neutronics
  - Thermonuclear burn
- Incorporating physical data
  - Neutron cross sections
  - Equation of state
  - Opacities
- Running on high-performance computers
  - World's first computer > 1 Petaflop
  - LANL is part of the Exascale Computing Project

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We Compare Our Simulations to Legacy Test Data

1054 nuclear tests (24 joint with UK)

Dual-Axis Radiographic Hydrodynamic Test Facility

- DARHT provides two beams of high-energy pulsed x-rays
- Allows testing the dynamics of implosions using non-nuclear components as a function of time
- These experiments are a critical part of validating our simulations

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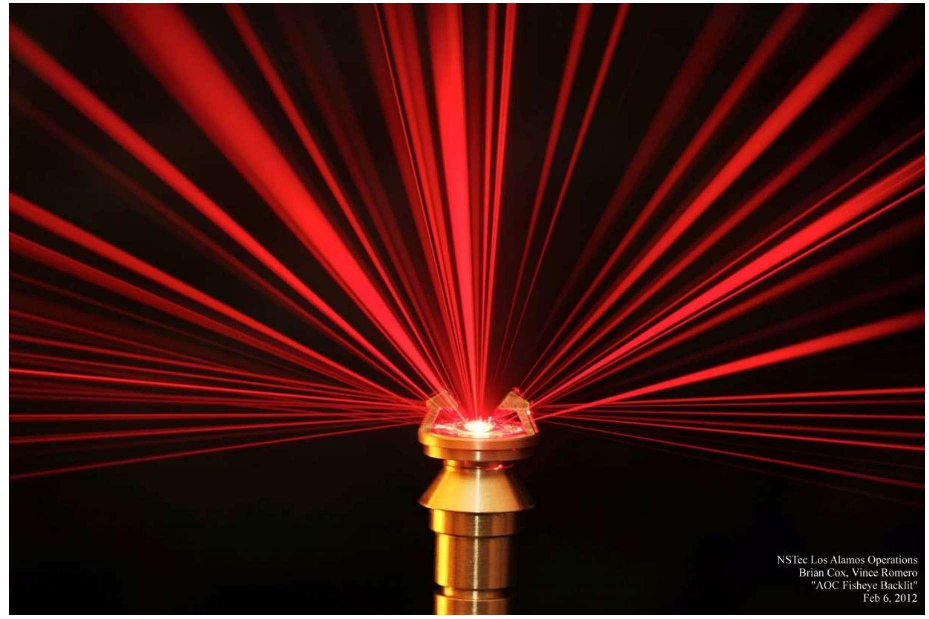
Sub-Critical Experiments Study Nuclear Materials

- Conducted underground at the Nevada National Security Site (formerly NTS)
  - The experiments are performed at a depth of 300 m to contain any radioactive release
- We can test the initial stages of implosion using plutonium
  - The amount of plutonium is reduced to avoid criticality
- Dynamic plutonium experiments provide important information on this material

High-Energy X-Rays and Laser Probes Provide Data



- Measure properties such as
  - Equations-of-state
  - Cavity formation and strength
  - Spall and damage
  - Ejecta
  - Material properties of aged versus new plutonium
  - Material properties of cast versus wrought plutonium
  - Metallurgy and its effects on other dynamic properties

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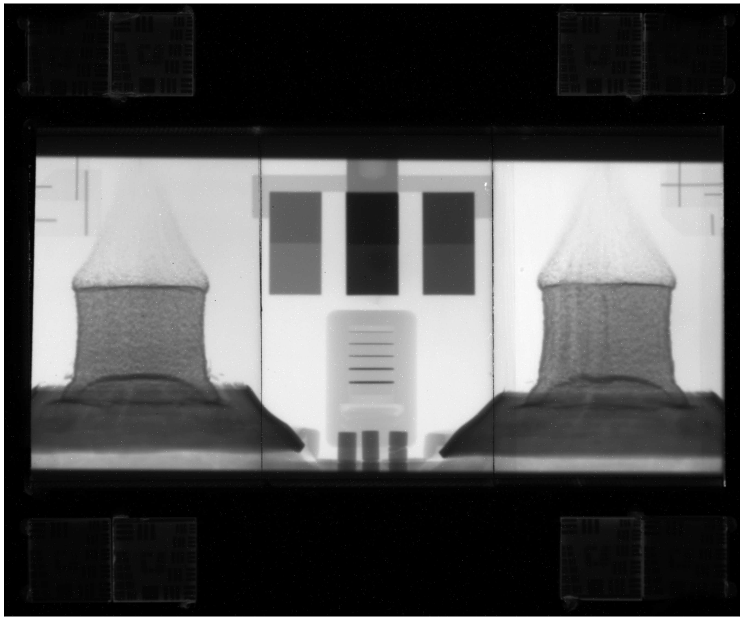
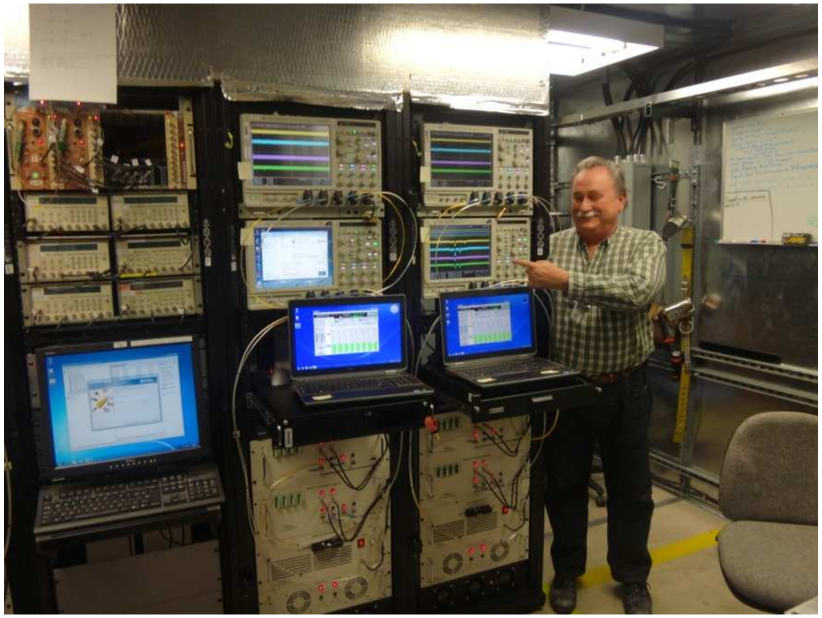
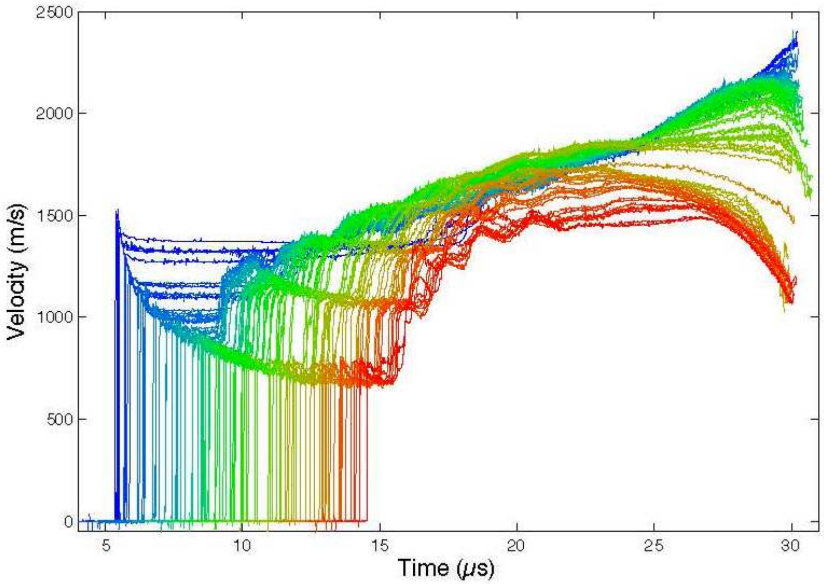
Example Radiographic Images



- Experiment designed to test reproducibility of dynamic experiments
- Two identical packages with non-nuclear materials were shot simultaneously
- High explosives drove shock through material from the bottom

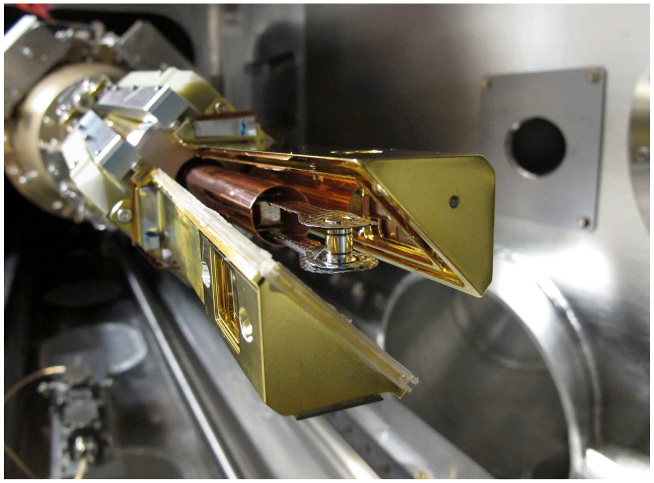
Multi-Point Photon Doppler Velocimetry

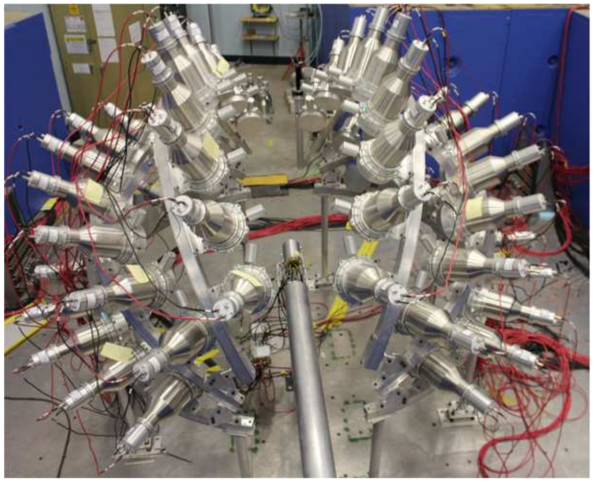




- Multiple laser beams allow velocity measurements of material at multiple points
- Doppler shift of beam reflecting from moving surface gives velocity
- Provides a rich data set (3M velocities) to compare to simulations

Small-Scale Experiments





Experiments improve the science behind nuclear weapons

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Proton Radiography Studies Dynamic Materials

- pRad uses 800 MeV proton beam to image dynamic experiments
- Beam can be pulsed to provide 40 images $\geq$ 100ns apart
- Images are analyzed to provide density information as a function of position and time

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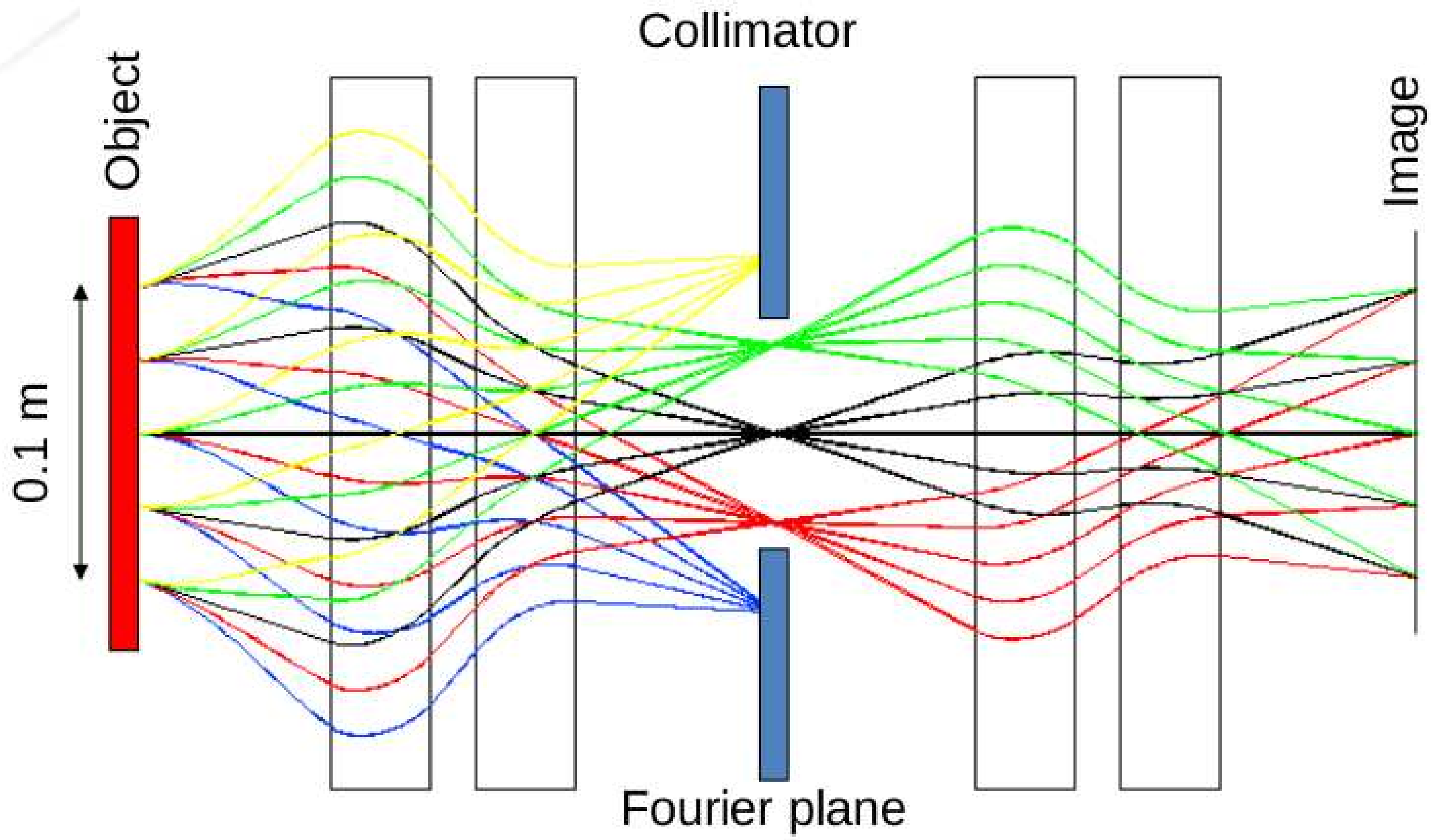
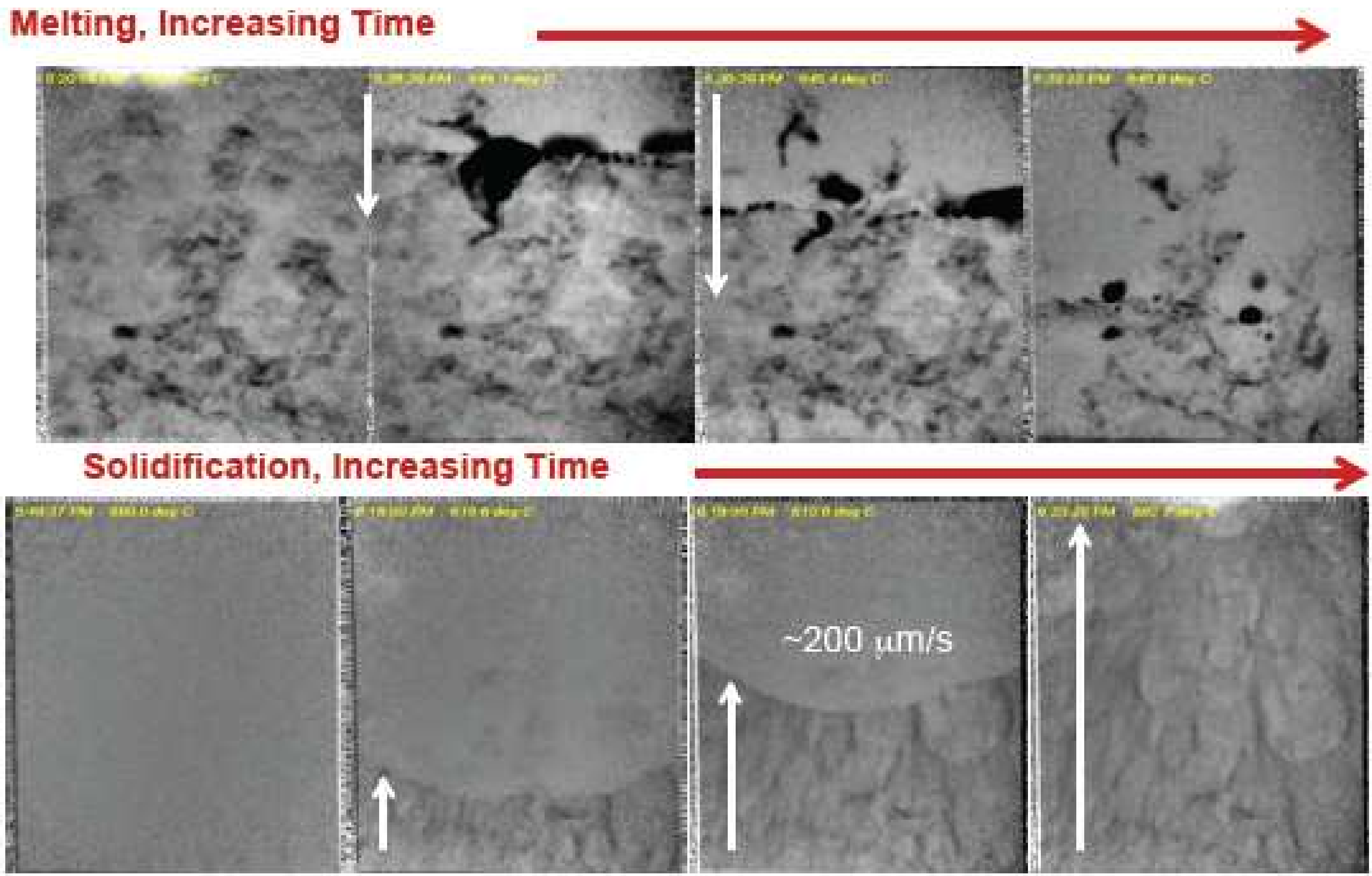
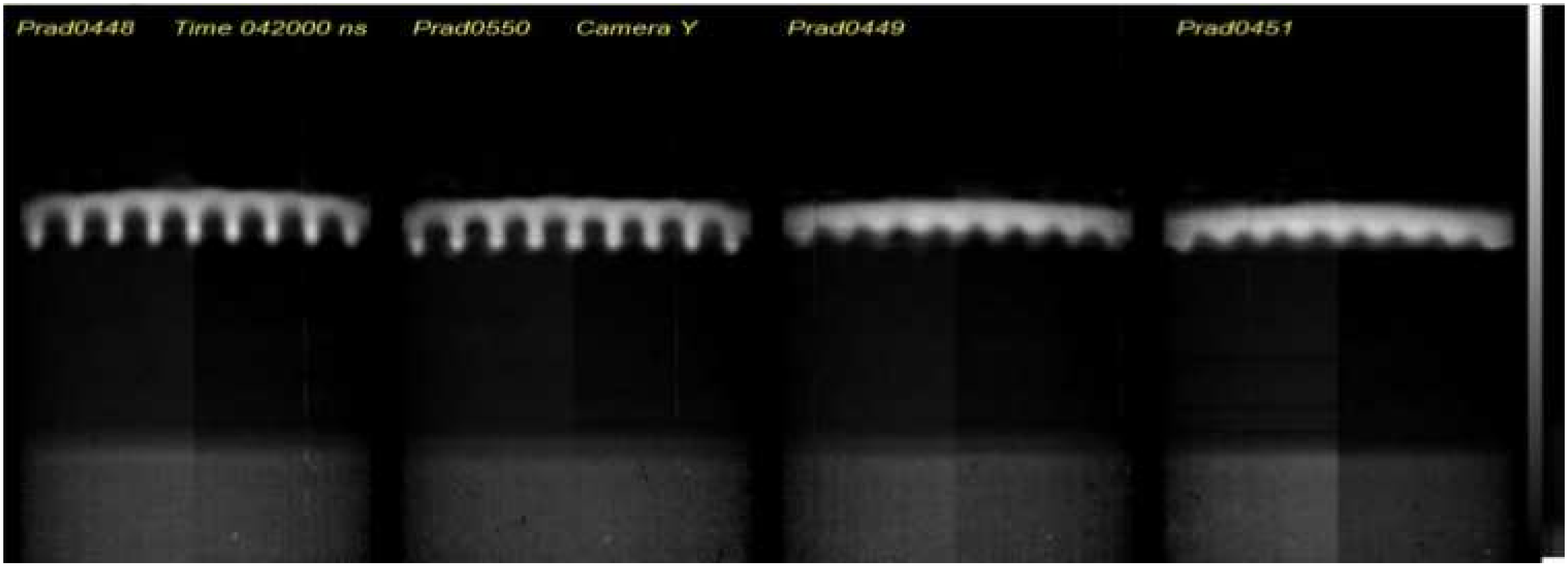
pRad Uses Multiple Coulomb Scattering



pRad Example: Melting and Solidification of Al-In Alloy

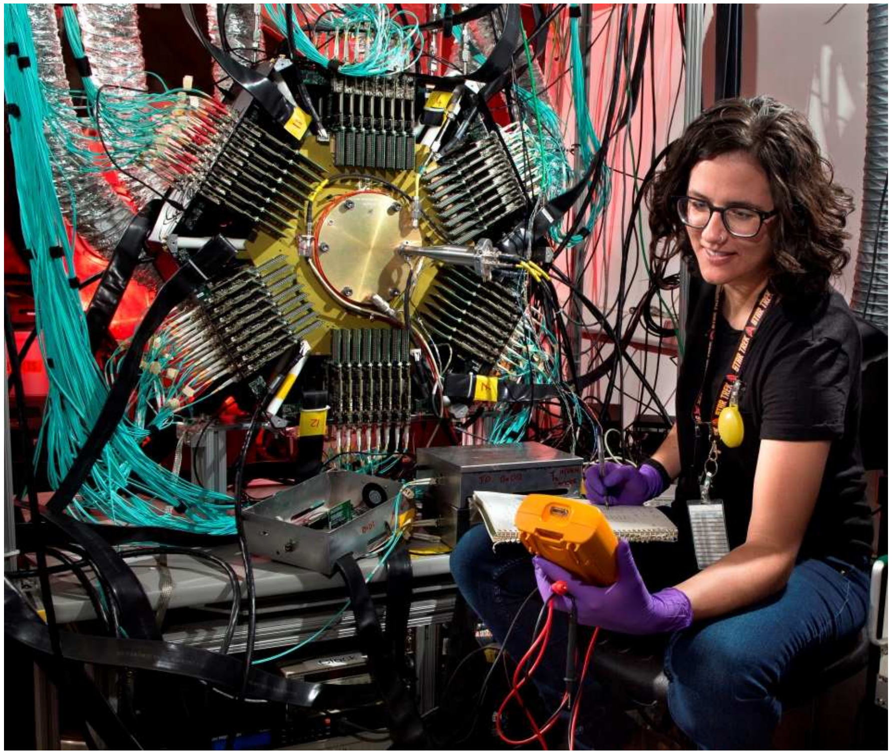


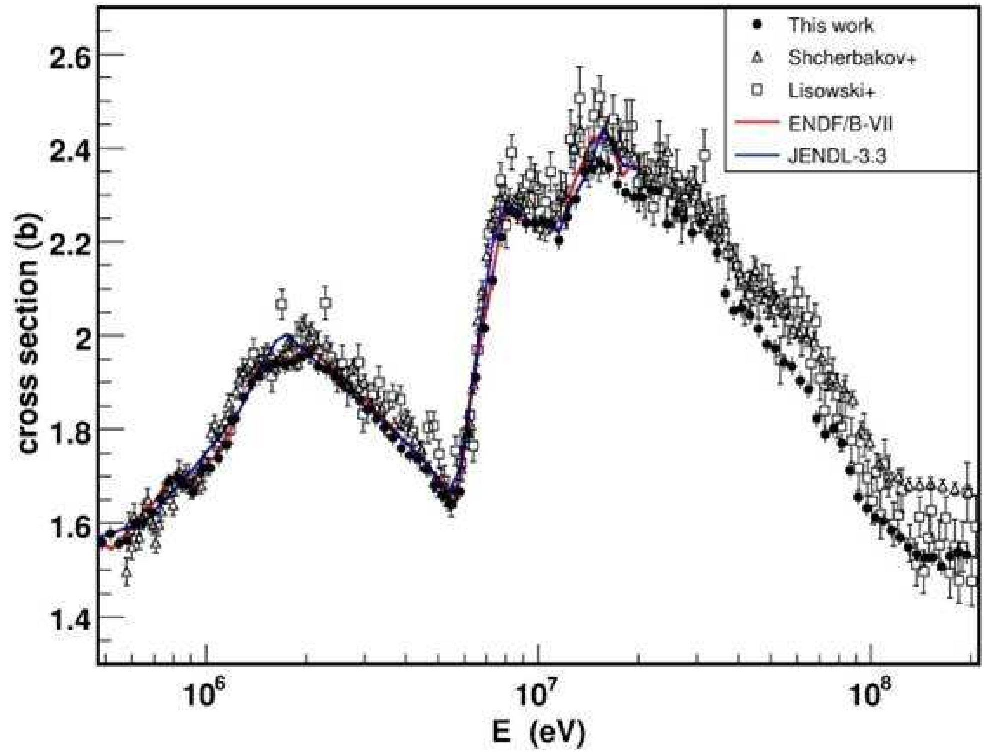
pRad Example: Instability Growth



- Shock applied to two materials with different densities

Precision Measurements of Nuclear Cross Sections





- The ^{239}Pu(n, f) cross section affects nuclear weapons performance
- Spread in existing data sets suggests uncontrolled or unaccounted for systematic uncertainties
- Lawrence Livermore National Laboratory and LANL are measuring this cross section at LANSCE to 1% precision

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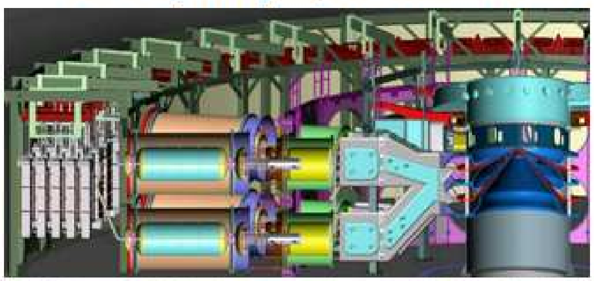
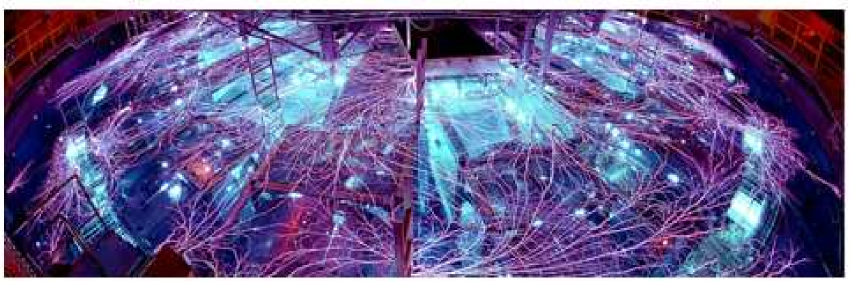
Experimental Facilities to Study Radiation Flow

Omega Laser Facility
Laboratory for Laser Energetics
University of Rochester
Rochester, New York

National Ignition Facility
Lawrence Livermore National Laboratory
Livermore, California

Z-Pinch
Sandia National Laboratory
Albuquerque, New Mexico





Summary

- Maintaining the U.S. nuclear stockpile without nuclear testing is very challenging
- We use a variety of science-based tools to perform this mission
- Large-scale multi-physics simulations running on high-performance computers have replaced nuclear testing
- Experimental data is crucial to calibrate and validate the simulations
  - Data from legacy nuclear tests
  - Large-scale integrated experiments
  - Sub-critical experiments
  - Small-scale experiments
- Many scientific disciplines contribute to maintaining the stockpile

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